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Using differential structure-from-motion photogrammetry to quantify erosion at the Engare Sero footprint site, Tanzania

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ABSTRACT

Hominin footprint sites are excellent sources of data that provide insights into early human physiology, anatomy, and social structures. They are also potential tourist attractions that are often situated in relatively under-developed parts of the world. Unfortunately, many footprint sites are also located in high energy environments and/or are pressed into poorly indurated sediments, which make them highly susceptible to erosion. This paper proposes a non-invasive and low-cost method employing Structure-from-Motion photogrammetry to quantify erosion rates in the absence of permanent ground control points. Using point cloud comparison algorithms between data collected at different times, it is possible to quantitatively analyze the locations, volumes, and rates of material loss. We applied this technique to several footprints within the Engare Sero footprint site in northern Tanzania to assess erosional change between 2010 and 2017. Our comparisons show that prints are vertically eroding at average rates ranging from 0.10 to 0.17 mm/yr with some localized areas experiencing much higher rates over shorter durations. We identify three primary modes of erosion: 1) flaking, 2) abrasion, and 3) boring of holes. Erosion appears to have occurred episodically with major events, such as flooding, separated by periods of relative stability. The methods presented here are valuable for paleoanthropologists to better understand how footprint erosion might adversely affect inferences regarding print-makers, and they are valuable for decision-makers, who can create conservation plans to better protect and maximize the utility of known hominin footprint sites.

1. Introduction

1.1. Importance of human track sites

Vertebrate tracks are often ephemeral, but under exceptional circumstances these traces may become part of the fossil record. When preserved, these ichnological data can provide avenues for important paleobiological insights regarding extinct taxa, including those related to anatomy, locomotion, social behaviors, and paleoenvironments (see Falkingham, 2014 for a review).

The record of tracks known from fossil hominins has been historically less robust than the ichnological records of some other fossil groups (e.g., dinosaurs) but the potential richness of the inferences that can be derived from hominin tracks has long been recognized. For example, immediately following the discovery of the 3.66 Ma hominin footprints at Laetoli (Leakey and Hay, 1979), analyses of these data were used to infer aspects of foot anatomy and locomotion (e.g., Day and Wickens, 1980; White, 1980; Charteris et al., 1981, 1982; Stern and Susman, 1983), social interactions (Leakey and Hay, 1979; Leakey, 1981), and the paleoenvironmental and depositional contexts (Leakey and Hay, 1979; Leakey, 1981).

More recently, new analytical methods have been developed and applied to reassess previously known hominin tracks (e.g., analyses of Laetoli tracks by Berge et al., 2006; Raichlen et al., 2010; Crompton et al., 2012; Hatala et al., 2016a), but a relative influx in hominin footprint discoveries over the past decade has provided new data and new questions regarding our evolutionary past. For instance, newly discovered 3.66 Ma trackways at Laetoli have revealed a higher level of size variation than previously

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recognized, which has implications for social behavior (Masao et al., 2016). Discoveries and subsequent analyses of 1.5 Ma footprints near Ileret, Kenya that are provisionally attributed to *Homo erectus* have suggested modern human-like patterns of foot anatomy and locomotion (Bennett et al., 2009; Hatala et al., 2016b), human-like social structures (Hatala et al., 2016b), and intensive use of lake margin habitats (Roach et al., 2016). Footprints dating to 1.0–0.78 Ma at Happisburgh, UK offer unique evidence of hominin occupation of northern Europe during the Early Pleistocene (Ashton et al., 2014). The co-occurrence of stone artifacts and hominin footprints on a 0.7 Ma surface at Melka Kunture, Ethiopia provides a rich record from which to infer behavioral patterns with different lines of synchronous data (Altamura et al., 2016). Sets of 10–16 ka tracks that were recently discovered in New Mexico, USA may directly record hunting behaviors of late Pleistocene humans (Bustos et al., 2018). These and other recent discoveries of human track sites have greatly expanded our knowledge of aspects of our evolutionary past. As the hominin track record continues to grow, methods to analyze them are sure to simultaneously expand, and more long-standing questions are likely to be addressed.

In addition to the scientific utilities listed above, footprint sites can also potentially increase tourism to otherwise undervisited regions of the world. Preservation infrastructure at footprint sites varies depending on the size and stability of a site as well as the tourism potential and financial resources available for development. Many localities have little more than an interpretive sign to indicate the location of a footprint site while others have pavilion structures, protected pits, and full museum displays on site (Lofgren et al., 2006; Roberts, 2008; Schmincke et al., 2009; Bennett et al., 2013). A balance must be reached between the scientific, cultural, and economic significance of a particular site and the expenditure of resources required to protect and develop it.

For both scientific inquiry and tourism potential, footprint sites must be considered a resource; one that is finite and, unfortunately, not permanent. Trackways are highly susceptible to erosion because they are often preserved in relatively soft and/or fine-grained sediments (e.g., Behrensmeyer and Laporte, 1981; Ashley and Liutkus, 2002). While the number of documented trackway sites has increased in the last several decades, some footprint sites have degraded (or been permanently lost) due to wind and rain (Marty et al., 2009; Bennett et al., 2013) or exposure to intense coastal erosion, where the prints only lasted a number of weeks (e.g. Formby Point, UK; Wiseman and De Groote, 2018, Happisburgh, UK; Ashton et al., 2014). Human-generated erosion through repeated excavation, vandalism, careless driving, and foot traffic has also been noted (Morgan et al., 2007; Bennett et al., 2013). Despite the most well-intentioned preservation efforts, sites of significant scientific and cultural importance have nonetheless degraded significantly through time (e.g., Laetoli, Tanzania; Demas and Agnew, 2006; Dalton, 2008). This degradation is of further import because many of the aforementioned paleobiological inferences derived from hominin footprints have relied in some way upon predictions of body size from footprint size. These inferences are therefore inherently tied to assumptions that footprint sizes are reliable records of true foot sizes. The integrity of this record, and the range of paleobiological questions to which footprint data can be applied, will diminish as footprints progressively erode and lose resolution (Wiseman and De Groote, 2018). There is clearly a desire to preserve footprints sites for scientific investigations, for cultural heritage reasons, and for potential economic development, but preservation is not always economically feasible and in some cases, not even possible. In many cases, the best option for long-term preservation may be digital curation.

1.2. Applications of SfM

With recent improvements in computing power and rendering software, it has become simpler and more expedient than ever to construct three-dimensional digital models of real-world objects and features using various Structure-from-Motion (SfM) algorithms (e.g. Luhmann et al., 2013; Mallison and Wings, 2014; Matthews et al., 2016; James et al., 2017). SfM is the process of rendering three-dimensional digital models from a series of overlapping images taken from different viewpoints. SfM produces three-dimensional models that allow for accurate and detailed quantitative measurements (Matthews, 2008; Bemis et al., 2014; Mallison and Wings, 2014). Furthermore, SfM models can be easily disseminated and archived as well as remotely manipulated and quantitatively analyzed. Historically, these models were simply nice visualizations. Today, however, with improved digital cameras and photogrammetric techniques, model resolution can be refined enough to make accurate measurements at the sub-mm-scale (Bemis et al., 2014). Current applications of SfM photogrammetry include, but are not limited to, estimating landslide volumes (e.g., Lucieer et al., 2013; Stumpf et al., 2015), monitoring active river systems (e.g., Javernick et al., 2014; Marteau et al., 2017), assessing cliff morphology (e.g., Ružić et al., 2014; Warrick et al., 2017), assessing large-scale erosion at recreation sites (e.g., Matthews, 2008) and measuring earthquake rupture zones and fault structures (e.g., Johnson et al., 2014). Here, we utilize differential SfM photogrammetry to quantify the rates and spatial patterns of erosion that are occurring at a hominin footprint site of archaeological and paleoanthropological importance.

The use of SfM photogrammetry to digitally preserve and distribute footprint morphological data has previously been applied to both human (Rüther et al., 2012; Bennett et al., 2016; Citton et al., 2017; Helm et al., 2018) and dinosaur track sites (Matthews et al., 2006; Petti et al., 2008; Pond et al., 2014; Citton et al., 2015; Marty et al., 2017; Belvedere et al., 2018). Furthermore, Adams et al., (2010) demonstrated that erosion detection could, hypothetically, be performed on footprint sites using a handheld laser scanner. While these studies used SfM photogrammetry for documentation and visualization of footprint sites, at the time of writing, no studies have thus far used differential SfM-based analyses over time to assess actual rates of change at trackway sites.

In addition to the loss of a potential tourist attraction, erosion of footprints can influence morphometric measurements made to estimate the stature and kinematics of print-makers (Wiseman and DeGroote, 2018). In this paper, we use SfM photogrammetry to quantify the rate of erosional degradation at the Engare Sero footprint site. The methods used here can provide quantitative data to improve methods for paleoanthropological inferences and assist in the creation of appropriate conservation plans.

2. Regional setting

Our research locality, the Engare Sero footprint site, is located in northern Tanzania, on the southern shore of Lake Natron (Fig. 1). Lake Natron sits just north of the Natron-Engaruka explosion crater area, which is bound on the west by the East African Rift escarpment and on the east by the extinct shield volcano, Gelai (Dawson and Powell, 1969; Dawson, 2008). Due to extension along the rift and associated crustal thinning since the Pliocene, the region is volcanically active (Bosworth, 1987; Dawson, 1992). Volcanic features within this region vary dramatically in size, age, and composition ranging from Pliocene shield volcanoes (e.g., Gelai) to intermediate composite volcanoes that are carbonatitic in composition (e.g., Oldoinyo L'engai; Dawson, 1962) to smaller tuff cones, rings, and explosion craters (e.g., Loolmurwak Crater; Dawson, 2008).

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